Wireless ad hoc networks access for aeronautical communications

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Wireless Ad Hoc Networks Access For Aeronautical Communications

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There is an increasing interest in the current aeronautical context to offer new services for civil aircraft passengers. For example, airlines want to offer their customers the opportunity to access the Internet, to manage their mails, to watch video on demand, to access corporate VPNs.... All these services represent a new type of air-ground communications called APC (Aeronautical Passenger Communications) in the ATN (Aeronautical Telecommunication Network) context. In this paper, we will show how an aeronautical ad hoc access network and satellite links can be used simultaneously for these communications.

I. Introduction

I.A. Existing solutions

The first system to provide Internet access to passengers used satellites. From 2004 to 2006, the Connexion-by-Boeing[1] system was installed on about 150 aircrafts. Due to economic reasons, the service was stopped in 2006. Since 2008, ARINC proposes another solution, called Oi for Onboard Internet[2]. Oi uses Inmarsat satellites with the SwiftBroadband service which offers throughput up to 432 kbps. In the same year, Panasonic offers a solution called eXConnect[3], that uses Intelsat satellites. OnAir[4] and Row44[5] have also develloped solutions using satellites. All these solutions have limits in terms of bandwidth, coverage and cost. Broadband Internet access for passengers requires the transport of large amount of data, with the additionnal problem of aircrafts concentration in some areas due to the geometry of aeronautical routes. Compared to ground-based solutions, satellite access provides low throughput. Furthermore, these solutions use geostationary satellites which don't cover the polar areas, where many aircrafts fly (e.g. between Europe and the United States). Lastly, the cost of satellite links, which caused the end of Connexion-by-Boeing, is generally very high.

Another way of providing In-Flight Internet is to use a direct link to the ground. Two such solutions exist, one called Gogo Inflight, is proposed by Aircell[6] since 2008 in the United States. The other one, proposed by Wi-SKY[7], will use Wi-MAX connexions between aircrafts and the ground. These solutions also have limits in terms of coverage and cost. The range covered by each ground station is limited and in oder to cover wide terrestrial area a lot of these ground stations have to be deployed. Obviously, these solutions will have a hard time covering oceanic areas. Furthermore, the cost of these solutions will increase with the number of ground stations, which will have to be deployed and maintained.

I.B. Our proposition : ADSL on air (AD hoc and Satellite Link)

The system architecture presented in this paper takes advantage of the well-known asymmetry property of Internet traffic generated by Web sites browsing, mails and video streaming in order to use two different

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technologies for uplink (aircraft to ground) and downlink (ground to aircraft) communications. The uplink relies on an aeronautical ad hoc network; the downlink uses a forward broadcast channel provided by geostationary satellites.

I.B.1. Aeronautical ad hoc access network

Presentation The interaction channel for the uplink is provided by an aeronautical ad hoc access network. The idea of such networks is to introduce wireless connections between aircrafts, each being able to establish a connection with other aircrafts nearby. Such a network doesnt need a heavy ground infrastructure and is self configuring and self healing. Each aircraft in the network can forward traffic to another aircraft or to a ground station, and therefore act as a router to transport data hop by hop to the destination. Hence, no centralized administration is needed to route exchanged data. Figure 1 represents the topology of such a network.

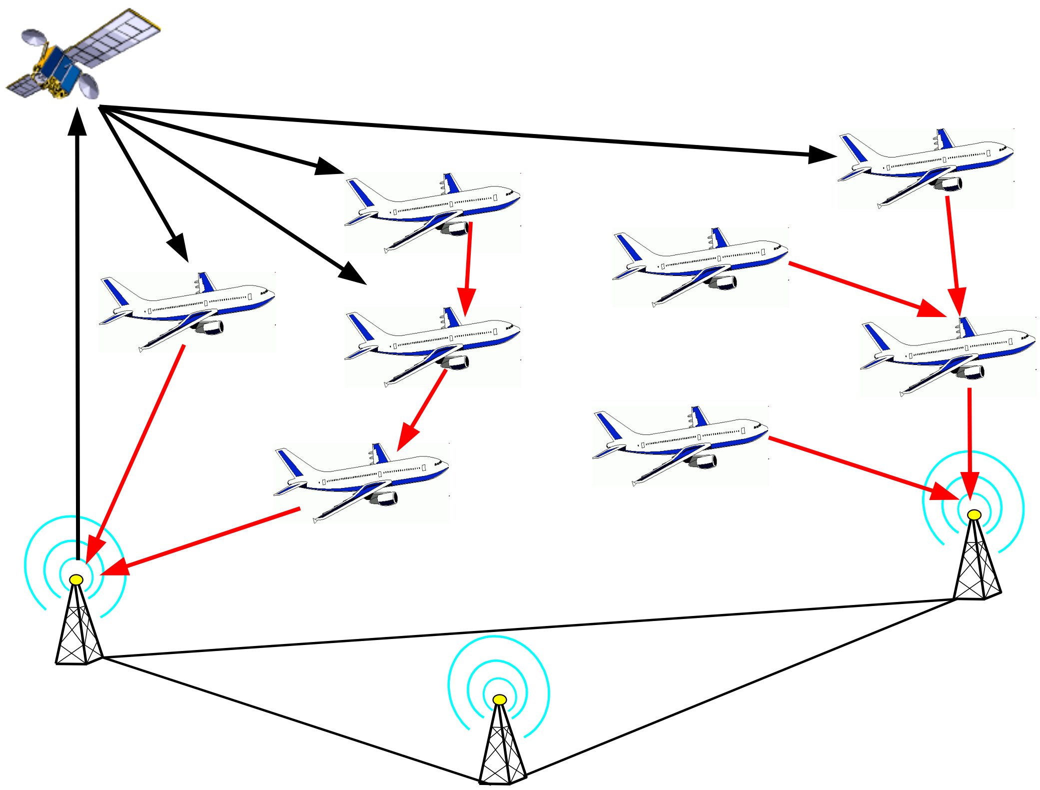

Figure 1. Topology of an aeronautical ad-hoc network with a forward channel by satellite

Related work Some projects have already studied aeronautical ad-hoc networks. Among these, the ATENAA Project[8,9] which began in 2004, deals with an aeronautical ad-hoc network which uses both directionnal and omni-directionnal antennas. The directionnal antennas are used to provide high throughput between aircrafts, at the cost of dealing with the problem of pointing and tracking an aircraft in flight. Omni-directionnal antennas on the other hand, are used to make the signalisation and to detect aircrafts in the area. The NewSky Project[10] which began in 2007, studies the feasibility of a global aeronautical network including all the means of communications of an aircraft, even connections between two aircrafts, to transport all data for the air traffic control, the airlines and passengers.

Known issues An aeronautical ad-hoc network brings up many issues that have to be considered. Firstly, there are issues at the physical and data link layers for the connection between aircrafts, and between an aircraft and ground stations. Then, there are issues at the network layer because the network, due to the high speed of aircrafts, may have a very dynamic topology, which could be a problem for the routing protocols.

In this paper, we aim at studying the feasibility of an aeronautical ad-hoc network with the aircrafts flying in the French sky. We consider a graph, whose nodes are the aircrafts, and whose edges are the connections between them, and we check that this graph is as highly connected as possible. We also want to estimate the percentage of connected aircrafts during a day. First, as we need accurate information on the air traffic during a significant duration, we present the aircrafts position data. Then, we focus on the link between aircrafts. And, finally, we present our results.

I.B.2. Satellite channel

The downlink uses a forward broadcast channel provided by geostationary satellites in Ku or Ka band and compliant with DVB-S2 ETSI standard. The use of DVB-S2 satellite links has the advantages to offer wide coverage and very high throughput. Moreover, aircrafts will only receive DVB-S2 TDM carriers from the satellite, the required performances of pointing and tracking the satellite are highly relaxed in the case of a receive-only antenna compared to a receive-transmit one. Frequency allocations are also simplified.

II. Dimensioning of the uplink and the downlink in OPNET

In this part, we estimate the traffic generated by all the passengers of an aircraft using a software called OPNET Modeler. This software is a network simulator. It allows us to compute the load of both ad hoc network and satellite links considering the number of connected aircrafts and the graph geometry.

II.A. Our model

The model we have developped for these simulations is composed of four different elements :

- a Wifi network called Wifi_subnet representing all the users onboard the aircraft
- link_emul that models the link between the aircraft and the ground
- a router to route data to the server
- a server to answer passengers' requests

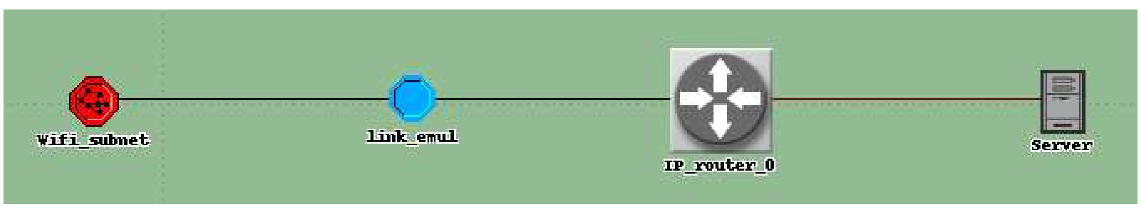

Figure 2. OPNET model

II.A.1. Wifi_subnet

The subnetwork in figure 3 represents all the users onboard a given aircraft. We consider that users are connected to the network by a Wifi access point. The number of users is a parameter of our simulations. Then, we can choose applications available for users. For now, we have only considered three applications implemented in OPNET Modeler : http for web browsing, mail and ftp to exchange files. Each aplication is customizable in OPNET. We have chosen the worst case for the three applications. Finally, each application starts randomly and ends at the end of the simulation.

II.A.2. Link_emul

For the link emulator in figure 4, we have chosen a very simple model. We separate the uplink and the downlink in order to introduice different delay for the two different links. For the uplink (from the aircraft to the ground), each packet use the aeronautical ad hoc network to reach the ground station, we consider that it introduices a 20 ms delay. For the downlink (from the ground to the aircraft), we use a geostationnary satellite, it introduice a 250 ms delay for each packet.

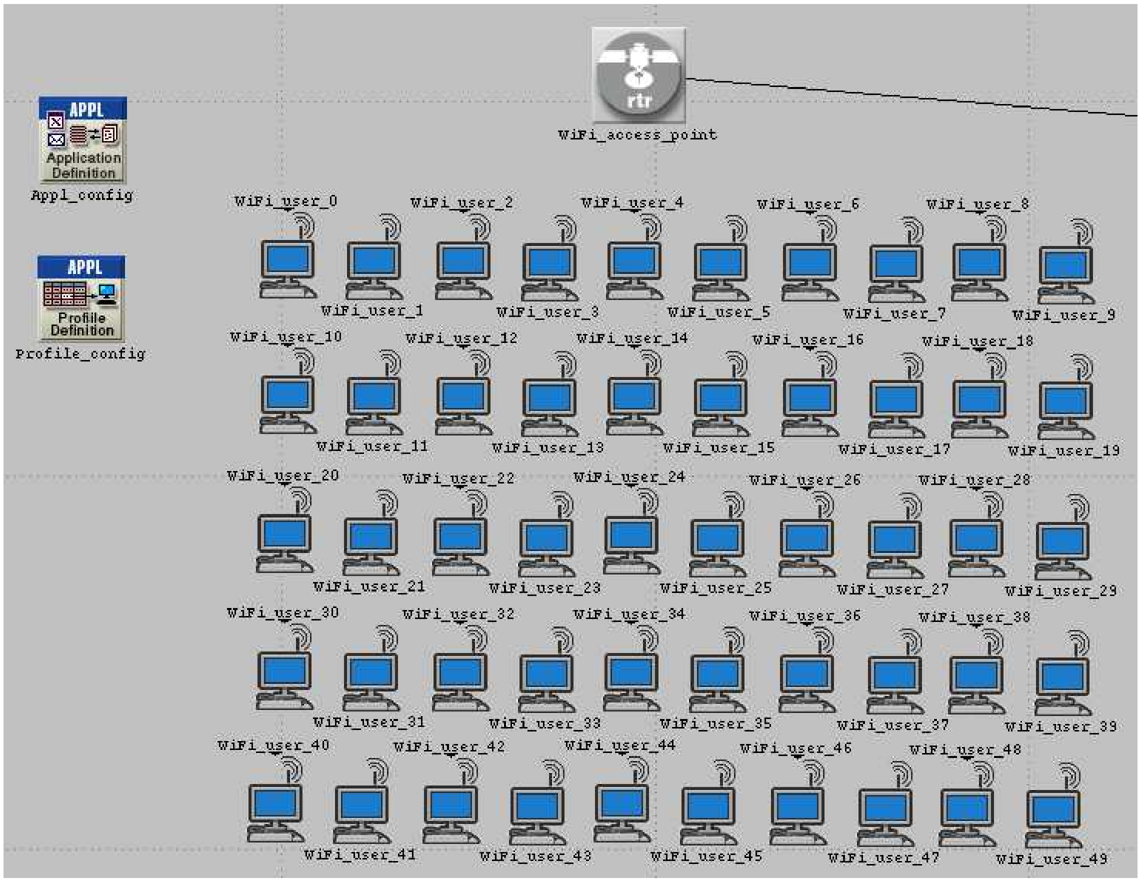

Figure 3. Wifi_subnet

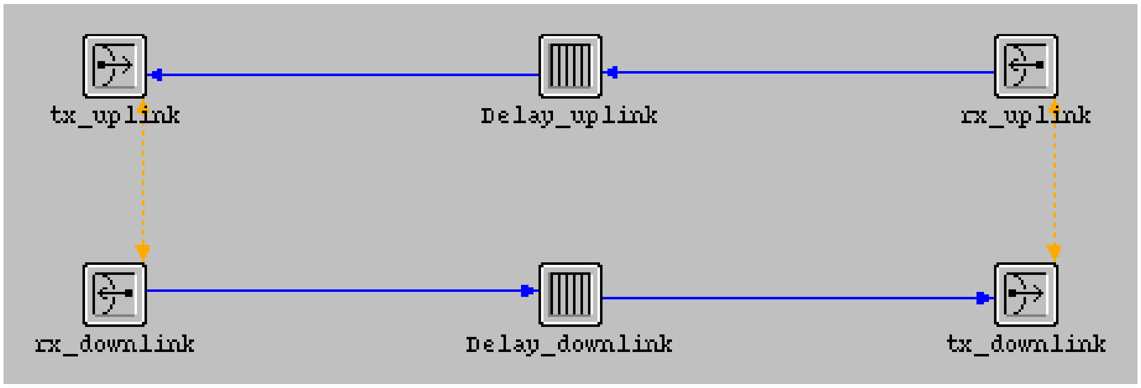

Figure 4. Link emulator

II.A.3. *The router and the server*

The router is here to route data to the server. The server is the same for all applications : http, ftp and mail.

II.B. Results

Figure 5 and figure 6 shows the throughput we have obtained for the uplink and for the downlink for 100 and 200 users in the aircraft.

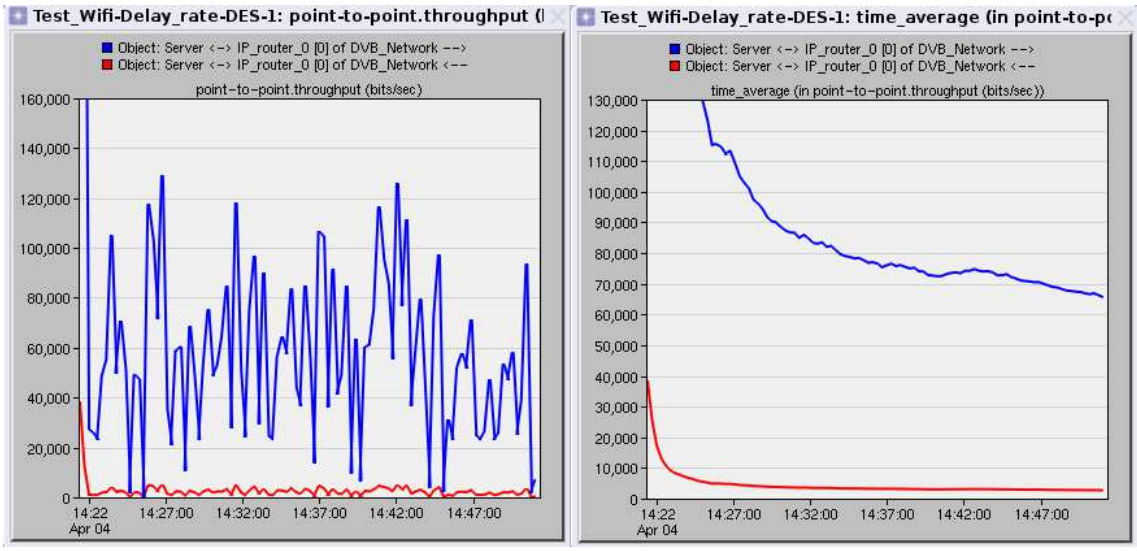

Figure 5. 100 users

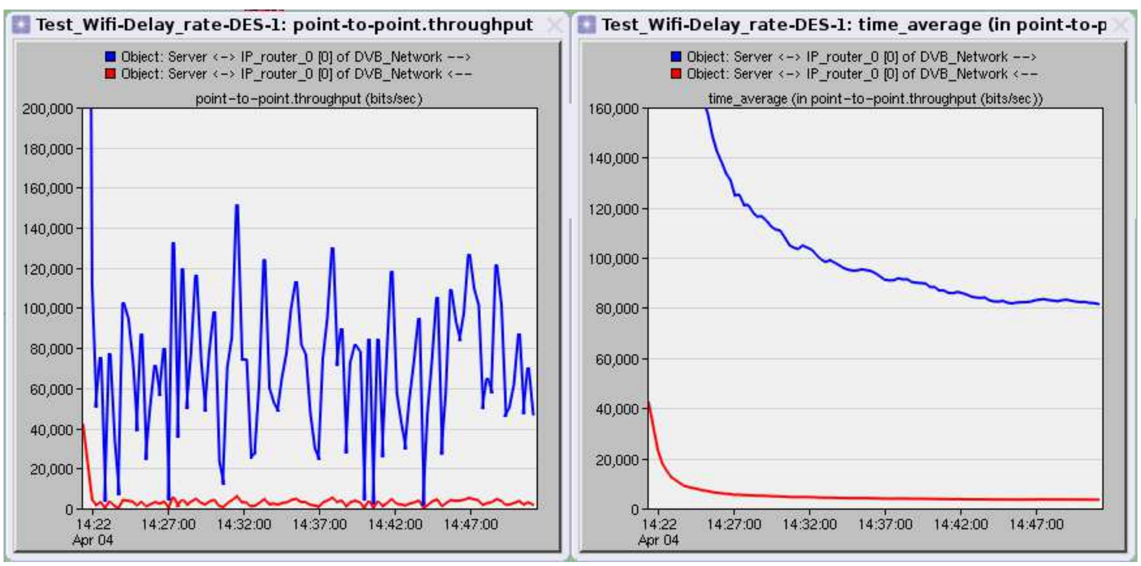

Figure 6. 200 users

For 100 users, the traffic generated by the three applications (http, ftp, mail) is about 5 kbps for the uplink and 65 kbps for the downlink on average. For 200 users, we have about 8 kbps for the uplink and 85 kbps for the dowlink. We can see here the asymmetry property of the Internet traffic generated by web sites browsing. Indeed, when we want to see a website, we only send a small http request, and we receive the whole page, which can be large. That's why the needs for the uplink and for the downlink are not the same.

III. Uplink (aircrafts to ground) performances evaluation

In this part, we first demonstrate the feasibility of the aeronautical ad hoc access network as this innovative aspect of the system design raises numerous challenging problems. Based on actual data for flying aircraft positions, we consider a graph whose nodes are the aircrafts and whose edges are the connections between them. A link budget gives us the maximum range between aircrafts that guarantee a given minimum throughput. We compute the percentage of connected aircrafts at each time during a day. This demonstrates that the graph is highly connected, meaning that the system offers a very high availability. The second step is the performance evaluation of the proposed approach to determine the available throughput of each aircrafts in the aeronautical ad hoc network.

III.A. Aircrafts position data

In Ref. 11–13, the study of the feasibility of an aeronautical ad-hoc network is based on a statistical approach of the number of flights in an area. They infer the density of aircrafts and then, by using a Poisson distribution, they obtain the probability of having at least n planes in an area around the aircraft. The probability of forming an aeronautical ad-hoc network is then the probability of always having at least two aircrafts in a sphere whose radius is the optical range. In Ref. 14, the feasibility study is based on a list of flight plans. Trajectories are interpolated between departure and destination airports with great circle arcs, which are actually the shortest paths between two points of the Earth sphere. For the present study, sources data on flight plan have been provided by the DSNA (Direction des Services de la Navigation Arienne). These data give the position of aircrafts flying through a considered geographic area, each 15 seconds during a given day.

III.B. Link between aircrafts

III.B.1. Choice of technology

First of all, a wireless technology is needed for the links between aircrafts, and between aircrafts and ground stations. We studied existing technologies, such as Wi-MAX and UMTS. Wi-MAX uses SOFDMA (Scalable Orthogonal Frequency-Division Multiple Access), whereas UMTS uses W-CDMA (Wideband Code Division Multiple Access). However, the Wi-MAX time and frequency division multiplexing might reach its limits because of the high density of aircrafts in some areas (e.g. around big European hubs), and a frequency reuse plan is beyond the scope of our study. A code-division multiplexing appears to be better for our system. Indeed, this will allow us to idendify each aircraft by a different code. Thus each aircraft would be able to communicate with several aircrafts simultaneously.

III.B.2. Link Budget

In Ref. 11–13, it is considered that a connection can be established between two aircrafts as soon as they can see each other. However, we want to guarantee that the connection has a minimum throughput of 100 kbps. That's why we have to make a link budget of the connection to find the maximum distance that guarantee this minimum throughput. This implies that if the distance between two aircrafts is smaller than this maximum distance, the available throughput will be higher than 100 kbps.

In Ref. 15, we can find a standard link budget for UMTS connections between a station and a mobile phone. We have changed some of the parameters of the UMTS technology to improve the throughput available for the user in our context.

First, we consider a chip rate of 20 Mcps, to be compared to 3.84 Mcps for UMTS. It means that we have a processing gain of $10.log\left(\frac{throughput_{chip}}{throughput_{data}}\right) = 23dB$. Then, we assume the use of omnidirectional antennas for aircrafts with 1 W emission power. Finally, we consider an interference margin of 3 dB. The resulting link budget is shown in table 1.

III.B.3. Propagation model

The maximum free space loss acceptable to guarantee a minimum throughput of 100 kbps for each connections is 142.02 dB. To find the distance corresponding to this maximum loss, we have to choose a propagation model. In Ref. 16, we can find some studies about UMTS performances in normal conditions, that is for a

Table 1. Link bubget

Transmitter		
Throughput (kbps)	x	**100**
Maximum emission power (W)		**1**
Mawimum emission power (dBm)	a	30
Antenna gain (dBi)	b	0
PIRE (?) (dBm)	c=a+b	30
Receiver		
Noise density (dBm/Hz)	d	-174.00
Receiver noise (dB)	e	5.00
Receivernoise density (dBm/Hz)	f=d+e	-169.00
Receivernoise power (dBm)	g=f+10*log(chip)	-95.99
Interference margin (dB)	h	3.00
Receiver interference power (dBm)	i=10*log(10^((g+h)/10)-10^(g/10))	-96.01
Global effective noise + interference (dBm)	j=10*log(10^(g/10)-10^(i/10))	-93.01
Treatment gain (dB)	k=10*log(chip/x)	23.01
Eb/No (dB)	l	3.00
Receiver sensibility (dBm)	m=l-k+j	-113.02
Receiver antenna gain (dBi)	n	0.00
Cable loss (dB)	o	1.00
Free space loss (dB)	p=c-m+n-o	**142.02**

connection between a ground station and a mobile phone. The simulations parameters are the difference of altitude between the station and the mobile phone, the vegetation caracteristics, the average height of the buildings, ... These won't apply to our study, as connections between aircrafts will be in direct line-of-sight, and if we ignore the atmosphere attenuation, we can use a propagation model in free space.

So we have $A = \frac{\lambda^2}{(4\pi d)^2}$, where A is the free space loss in dB, λ the wavelength in m and d the distance in m. Thus we have $A_{dB} = 32.44 + 20log(f_{MHz}) + 20log(d_{km})$. For several frequency values, we obtain the following distance :

Table 2. Maximum distance between two aircrafts (100 kbps)

Free space losses (dB)	142.02	142.02	142.02	142.02
Frequency (GHz)	2	3	4	5
Distance (km)	150.65	100.43	75.33	60.26

We can see that at 2 GHz, which is a frequency close to the frequency used by the UMTS technology, an aircraft can establish a connection with an other aircraft if the distance between them is shorter than about 150 km. But this distance is very dependant on the frequency, which is yet to specify. That's why the maximum distance between two aircrafts for the establishment of a connection will be a parameter of our simulations, as in Ref. 14.

III.C. Influence of the communication range

In this part, we present our results for a day of June 2007. This day, 9435 aircrafts have flown over the French territory and we have their positions each 15 seconds for all the day. Figure 7 shows the number of in-flight aircrafts accross the day.

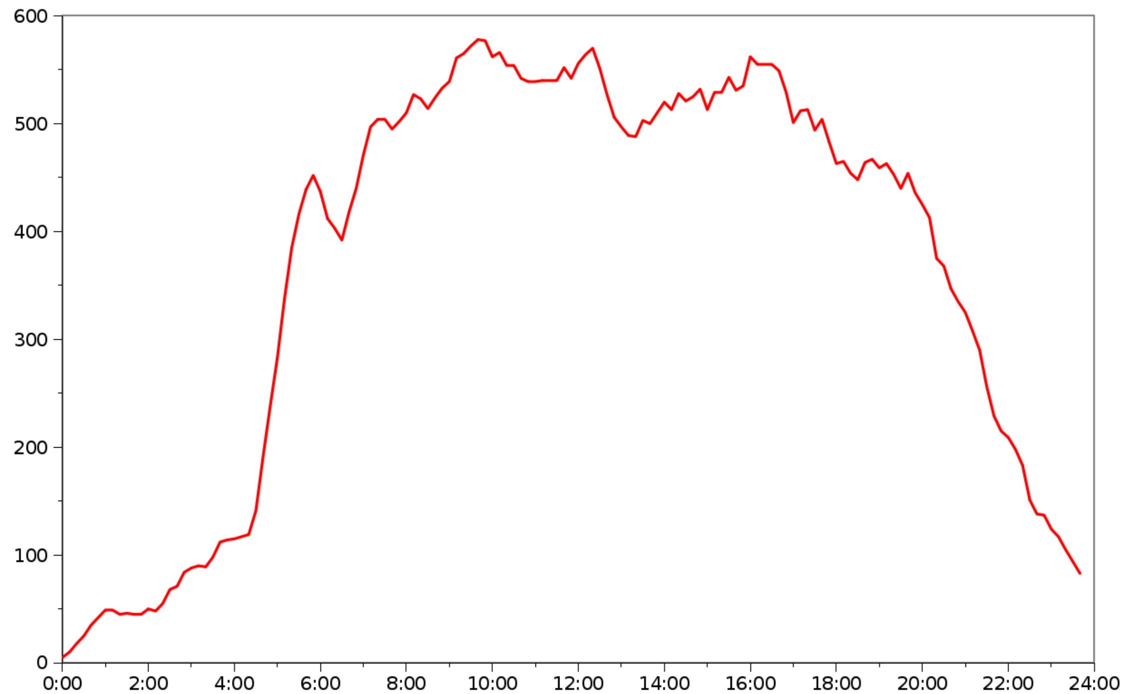

Figure 7. Number of inflight aircrafts

We can distinguish two different periods : the first one between 6 a.m. and 9 p.m. where the air traffic is dense and the second one covering the rest of the day where there are always less than 200 aircrafts in the sky. During this last period, it is obvious that it will be difficult to maintain the service for all aircrafts.

We make the assumption that the ground stations will be placed near the five french CRNA (Centre en Route de la Navigation Arienne), whose positions have been chosen by the ATC administration to fairly share the amount of in-flight aircrafts.

The first simulation results highlight the influence of the maximum distance between two aircrafts to establish a connection on the percentage of connected aircrafts. In figure 8, we can clearly see that the longer the range is, the higher the percentage of connected aircrafts will be.

Table 3 shows the average percentage of connected aircrafts during the whole day and between 6 a.m. and 9 p.m.

Table 3. Range influence

Range (km)	Average ratio (%) of connected aircrafts between 0 a.m. and 12 p.m.	Average ratio (%) of connected aircrafts between 6 a.m. and 9 p.m.
50	47.55	59.97
75	73.61	89.68
100	84.63	96.50
125	91.00	98.69
150	94.72	99.41

We underline the fact that for a range longer than 125 km, more than 90% of aircrafts are connected. Between 6 a.m and 9 p.m., even a 100 km range is enough to connect more than 95% of aircrafts.

These results are promising, but not all aircrafts are connected, even for a range of 150 km. Actually, what we have observed is that during the night, unconnected aircrafts can be found everywhere in the area we consider, because the aircraft density is not high enough to guarantee a connected network. One solution to

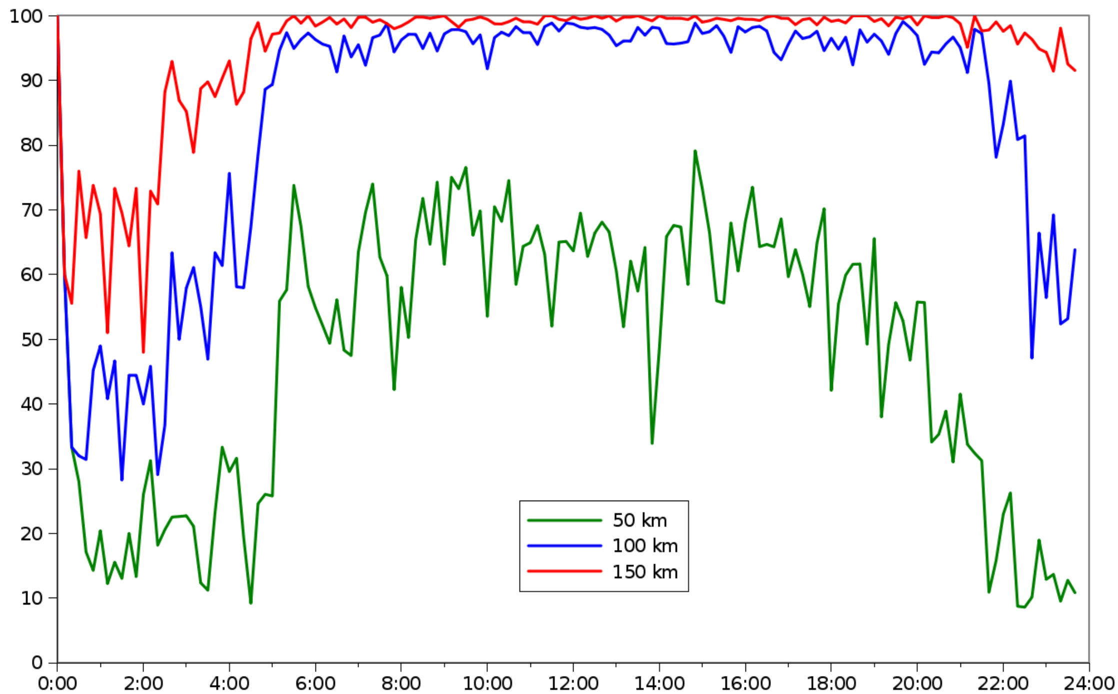

Figure 8. Range Influence

connect them would be to increase the communication range of each aircraft, even if it leads to throughputs lower than 1 Mbps. Though, as there will be few aircrafts, this throughput might be enough. During the rest of the day, the density of aircrafts is higher and it is easier to keep the network connex. We noticed that all unconnected aircrafts were located on the edge of the area we study, meaning that they would probably be connected if we consider aircrafts flying in Europe.

III.D. Routing

To determine the available throughput per aircraft, a path to the ground station has to be chosen. As the routing protocol[17] is not yet defined, we use the shortest path to the closest ground station, given by the Dijsktra algorithm. We obtain a list of edge representing the path from each aircraft to the ground station. Then, we will present two approach to estimate the available throughput per aircraft.

III.E. Maximum available throughput per aircraft

The first approach is to determine the maximum throughput for a given aircraft. We consider that only this aircraft is sending messages. With the Dijsktra algorithm, we have obtained a path to the ground station. And with the length of each edge of this path, we can determine available throughput on each link. We use the link budget and the free space propagation model, which gives :

$$A_{dB} = 142.02 - 10 \cdot log(throughput_{Mbps})$$

$$A_{dB} = 92.44 + 20 \cdot log(f_{GHz}) + 20 \cdot log(d_{km})$$

We have :

$$throughput_{Mbps} = 10^{\frac{49.58 - 20 \cdot log(f_{GHz}) - 20 \cdot log(d_{km})}{10}}$$

And finally :

$$throughput_{Mbps} = \frac{10^{4.958}}{f_{GHz}^2 \cdot d_{km}^2}$$

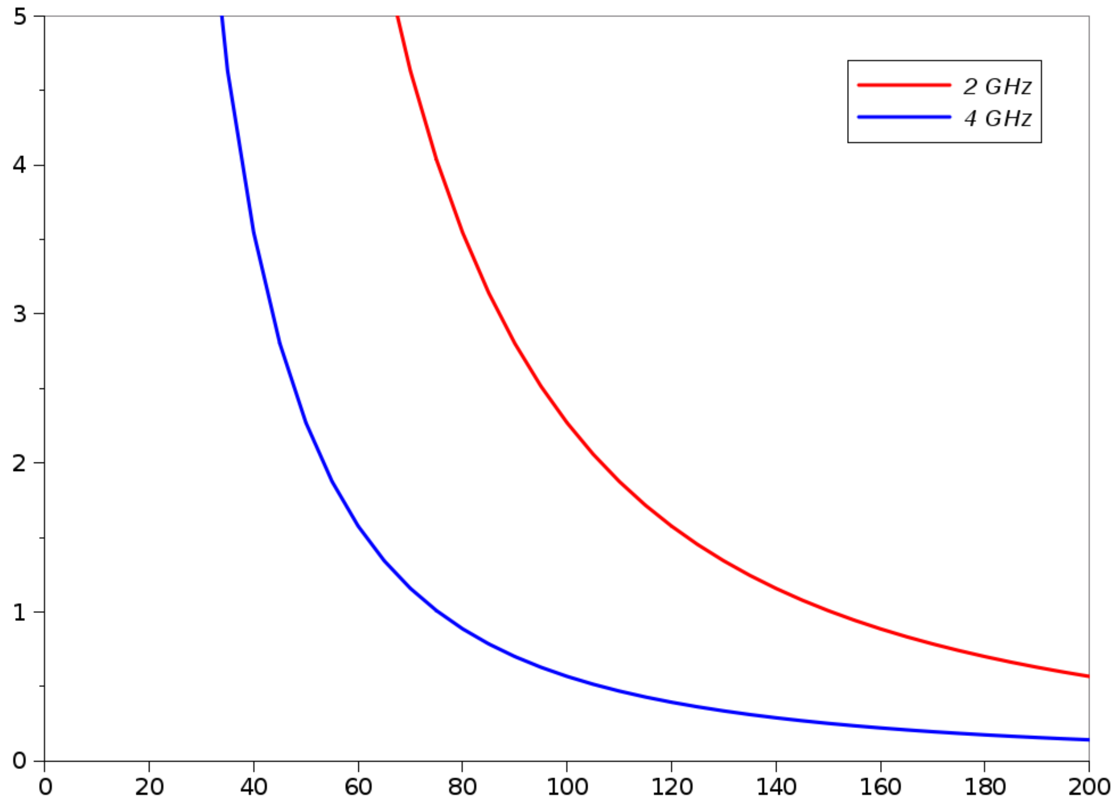

Figure 9. Throughput (Mbps) evolution with the distance (km)

Figure 9 shows the evolution of the throughput with the distance for two frequencies.

Theoretically, the throughput decreases in $\frac{1}{x^2}$ with the distance. But even if the two aircrafts are very close, the throughput cannot be infinite because of the limited emission spectrum. For now, we consider that the maximum throughput is 5 Mbps. Now, we can associate the length of the connection with the available throughput. And, as the throughput decrease with the distance, we only need the length of longest edge of the path to the ground station. This edge is the bottleneck of the connection between the aircraft and the ground station. Figure 10 shows the maximum available throughput we obtain for all the flights.

We notice that the minimum throughput for all the flights is about 2 Mbps. That is due to the fact that in this simulation, we have chosen a maximum range of 100 km for the aircrafts and this distance gives a throughput of about 2 Mbps at 2 GHz.

III.F. Fairly shared available throughput per aircraft

In the first approach, only one aircraft sent messages. Of course, this situation is very unrealistic. We now consider that all aircrafts can send messages, which implies that the available throughput of a link will be shared. We still consider that our routing protocol choose the shortest path to the closest ground station of the aircraft. Using the same method as in the first approach, the throughput/distance relation is calculated for a 2 GHz frequency. Finally, we consider that on each edge, the maximum throughput is fairly divided between all aircrafts whose traffic uses this edge. Thus we can estimate the available throughput for each aircraft at each instant of our simulation. Figure 11 shows the average and the minimum throughput for all aircrafts at each instant of the day.

We see that the average throughput is about 1 Mbps or more during the day. However, the standard deviation is high. That is probably due to the fact that we use the shortest path to the destination. This leads to a congestion around the ground stations. Aircrafts near the station have a higher throughput than those far from the station. In further study, the routing protocols will have to take this problem into account. We will probably have to use longer path to balance the load of the network on the different links.

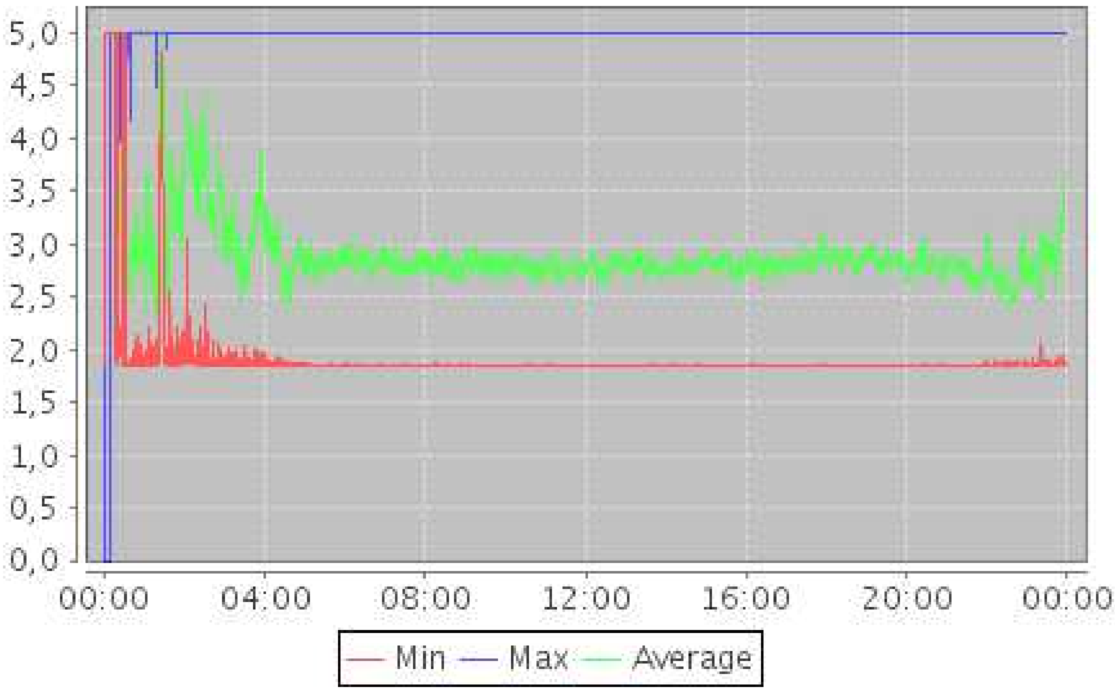

Figure 10. Maximum available throughput per aircraft

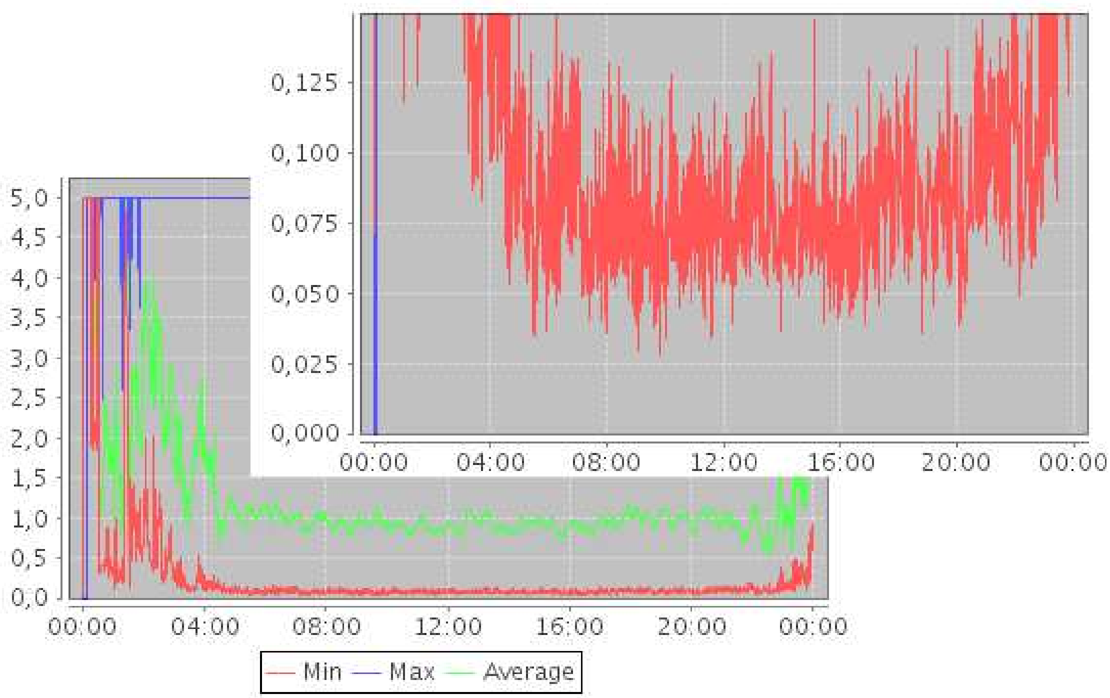

Figure 11. Fairly shared available throughput (Mbps) per aircraft

In figure 11, we can see the minimum throughput af all aircrafts is always higher than 25 kbps. It means that all aircrafts have a higher throughput that the one found in the OPNET simulations for the uplink, which was about 8 kbps for 200 users, as shown in figure 6.

III.G. Interference estimation

III.G.1. Method

In the link budget presented in table 1, we have considered $\frac{E_b}{N_0} = 3dB$ to obtain a throughput of 100 kbps. We decided to check whether this level is reached or not. We have $(\frac{E_b}{N_0})_{dB} = G_e + (\frac{S}{N})_{dB}$, where $(\frac{E_b}{N_0})_{dB}$ is the energy per bit to noise power spectral density ratio, G_e is the processing gain and $(\frac{S}{N})_{dB}$ the signal-to-noise ratio. To make sure that we have a good $\frac{E_b}{N_0}$ ratio, we have compute the $(\frac{S}{N})_{dB}$ ratio of each connexion in the network.

We consider here the worst case : each aircraft send data constantly. We consider that each aircraft is connected to the closest ground station by the shortest path given by the Dijsktra algorithm. We then consider that each aircraft has an emission power of 1W. In fact this value doesn't matter because what we want here is the signal-to-noise ratio of each connexion, ie the ratio between the power of the given signal and the power of noise and other interferent signals. We don't consider here any control power algorithm : all the aircrafts have the same emission power and they always use the same power, whether the destination is near or far.

Finally, we compute for each aircraft the SNR of each useful signal, considering that the power of each signals decrease in $\frac{1}{d^2}$ with the distance.

III.G.2. Results

Figure 12 shows the average of the signal-to-noise ratio of all useful signals during a day, considering different ranges for aircrafts.

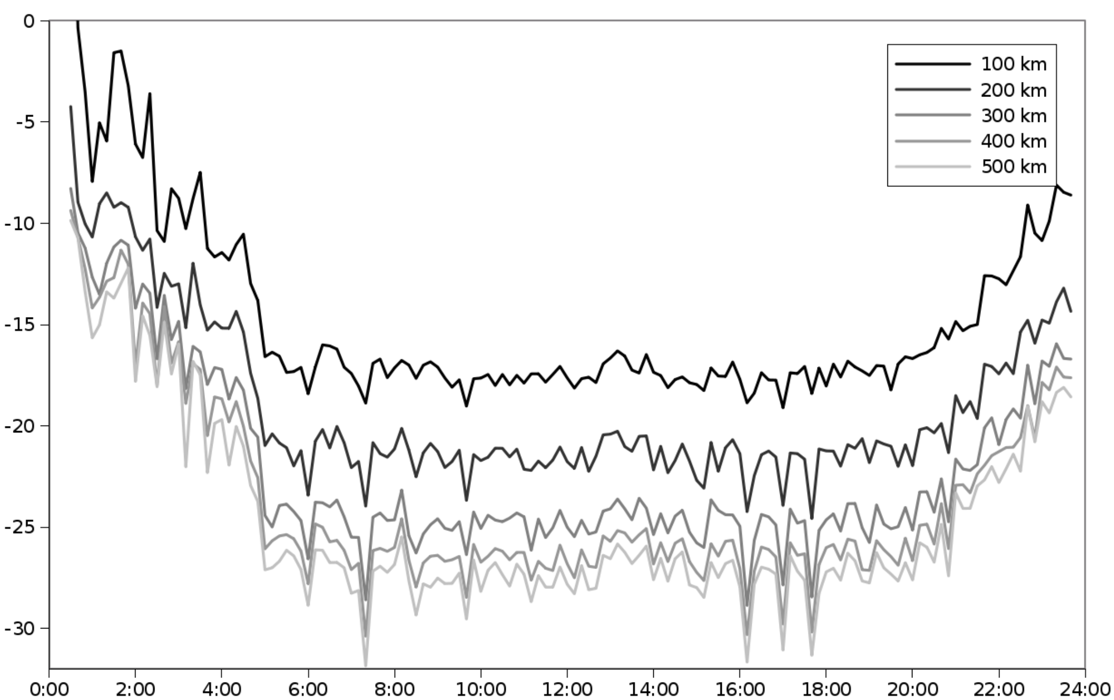

Figure 12. Average of the signal-to-noise ratio (dB) of all useful signals during a day for different ranges

Figure 13 shows the standard deviation of the signal-to-noise ratio of all useful signals during a day for different ranges.

Figure 14 shows the minimum of the signal-to-noise ratio of all useful signals during a day for a range of 100 km.

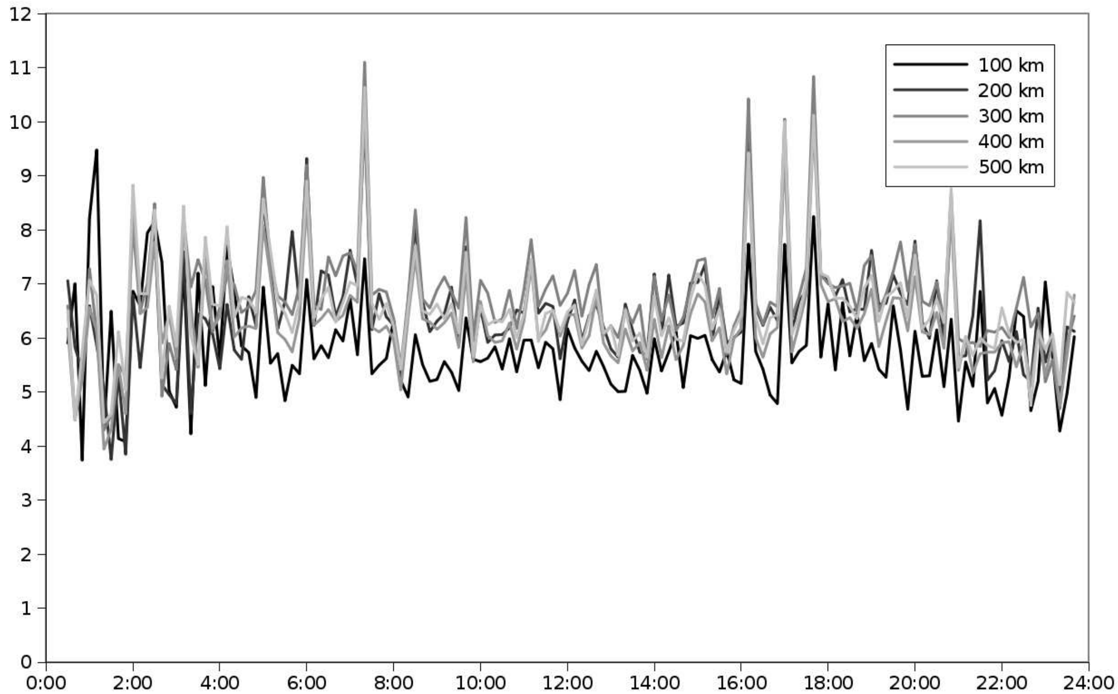

Figure 13. standard deviation of the signal-to-noise ratio of all useful signals during a day for different ranges

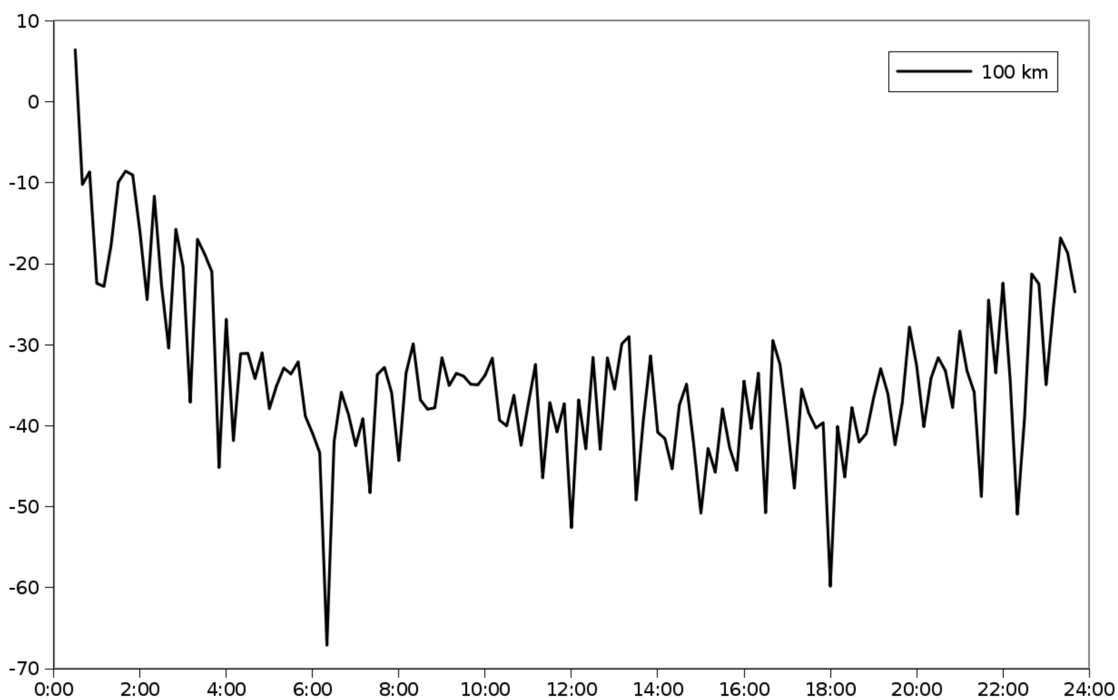

Figure 14. Minimum of the signal-to-noise ratio of all useful signals during a day for a range of 100 km

We can see that the shortest the maximum range is, the better is the signal-to-noise ratio and the standard deviation. It means that if we want to reduice the interference level in our system, we have to use short connexions between aircrafts. It will have to be taken into account in our future works on the routing protocol. But as we can see in figure 8, if the maximum range of each aircraft decrease, the percentage of connected aircrafts in the network decrease too. Thus the optimal range is about 100 km. For this range, the signal-to-noise ratio is about -17 dB on average, with a standard deviation of about 5 dB, but the minimum is about -40 dB. To dimension our system, we have to choose a maximum signal-to-noise ratio. We have chosen -25 dB. Indeed, with a signal-to-noise ratio of about -17 dB on average, with a standard deviation of 5 dB, this value allows us to guarantee the great majority of the connexion.

IV. Downlink (ground to aircrafts) performances evaluation

ENAC and ISAE are involved in the Aerospace Valley FAST (Fiber-like Aircraft Satellite telecommunication) project[18]. Considering a forward broadcast channel provided by a geostationary satellite in Ku or Ka band and compliant with DVB-S2 ETSI standard, a link budget made for this project gives a data rate of 55.8 Mbps in Ku band. Moreover, we can use several DVB-S2 carriers, meaning that we have a high available throughput for the downlink.

V. Conclusion and Future Work

In this paper, we have considered an hybrid solution with an aeronautical ad hoc access network and a satellite return channel to provide In-Flight Internet for passengers. The objective was to demonstrate the feasibility of such a network. We have shown that with a 150 km range, 99.41% of aircrafts were connected between 6 a.m. and 9 p.m. Then, we have shown that, even with a simple routing protocol such as the shortest path, we offer a higher throughput to each aircrafts than the throughput generated by 200 users for the uplink and the downlink.

For our future works, we will have to study the routing algorithm in order to reduce the interference level of the system. For example it would probably be a good idea to give priority to paths that use short connexions to reach the ground station. Then, because of a new tendency in the Internet (i.e. interractive multimedia applications), an exclusively satellite-based return channel may be too stringent and inefficient for some services. For example a visioconference needs a shorter delay than the one introduced by a geostationary satellite. For such applications, we will study a second topology where the ad-hoc network is used as the return channel for interactive flows. The satellite will only be used for the bulk transfer flows. This last proposal is shown in figure 15.

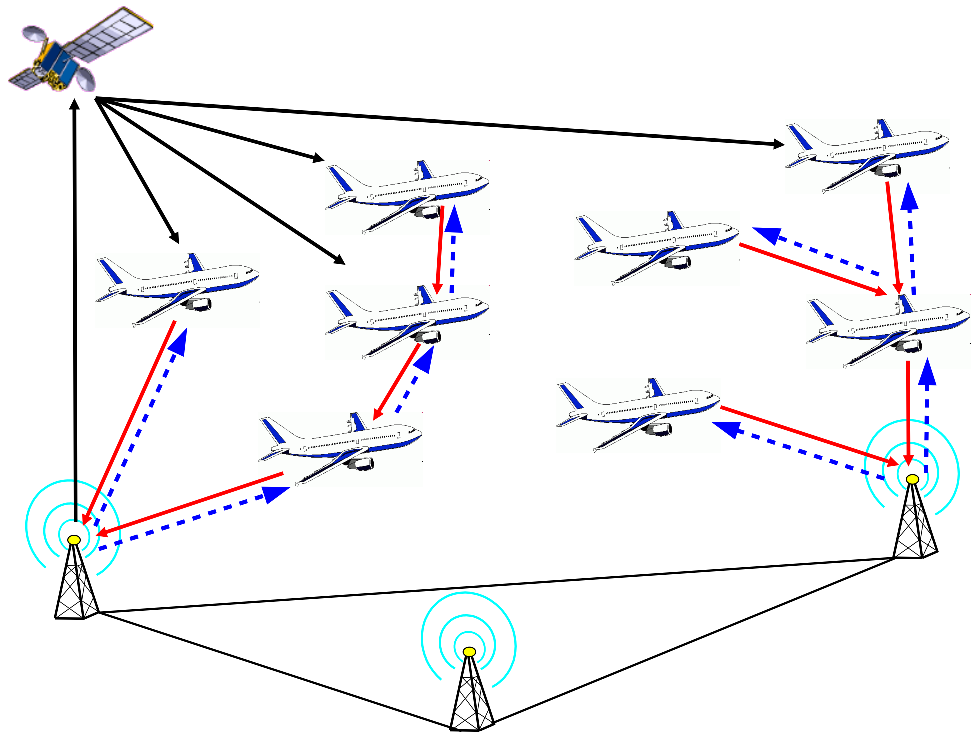

Figure 15. Hybrid topology

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